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Retrieval of cloud parameters by multiple observations in the near-infrared under conditions of varying solar illumination

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ABSTRACT

A method is presented to remove the thermal component of near-infrared radiances observed from geosynchronous satellites. The resulting solar component is then used to retrieve the effective radius of persistent marine stratiform clouds.

1. INTRODUCTION

It is becoming increasingly recognized that parameterization of radiative transfer in clouds is an important component of numerical climate models.[1,2] These parameterizations require a knowledge of the global distribution of cloud parameters important to radiative transfer. Numerous investigators have devised methods for determining cloud properties by remote sensing techniques.[3,4,5,6,7] However, many of these techniques use experimental instruments in aircraft overflying the clouds, and cannot as yet provide cloud properties over large areas. There is a long history of near-infrared observations of the earth from space.[8] This region of the upwelling earth's spectrum contains thermal radiation at night, and a mixture of thermal and scattered solar radiation during the day. Daytime observations have largely been eschewed in quantitative studies due to the difficulties in separating the thermal and solar components. This paper presents a technique to remove the thermal component of daytime near-infrared radiances, and use the resulting solar component to retrieve a measure of the cloud microphysical structure.

2. METHODOLOGY OF RETRIEVAL

The method employed here makes use of the peculiarities of the viewing geometry from geosynchronous orbit (Figure 1). The satellite views a cloud feature twice over a short period of time during which the thermal structure, location, and radiative characteristics of the cloud change little. During this time interval, the sun's location changes in the sky. The solar component of the radiation scattered by the cloud and sensed by the satellite changes because the solar zenith angle modulates the amount of radiation impinging on the cloud, and the combination of the solar zenith and azimuth angles result in a different scattering angle. Further, the path length from space to the cloud changes. However, if during this interval the thermal component of the sensed radiance is essentially unchanged, the two observations can be differenced, and the thermal components cancel. The result is the difference in the scattered solar component.

Clouds are not composed of uniformly sized particles, but rather have distinctive distributions.[9] Scattering parameters are not. for the most part, dependent upon the cloud particle size distribution, but rather upon an effective radius defined as [10]

$$r_e = \frac{\int_0^\infty r^3 n(r)dr}{\int_0^\infty r^2 n(r)dr}. \tag{1}$$

The effective variance is defined as [10]

$$v_e = \frac{\int_0^\infty (r-r_e)^2 r^2 n(r)dr}{\int_0^\infty r_e^2 r^2 n(r)dr}, \tag{2}$$

where n(r) is the cloud particle size distribution as a function of the particle radius r. In this study, the particle size distribution is chosen to be a modified gamma distribution [11] in the form [12]

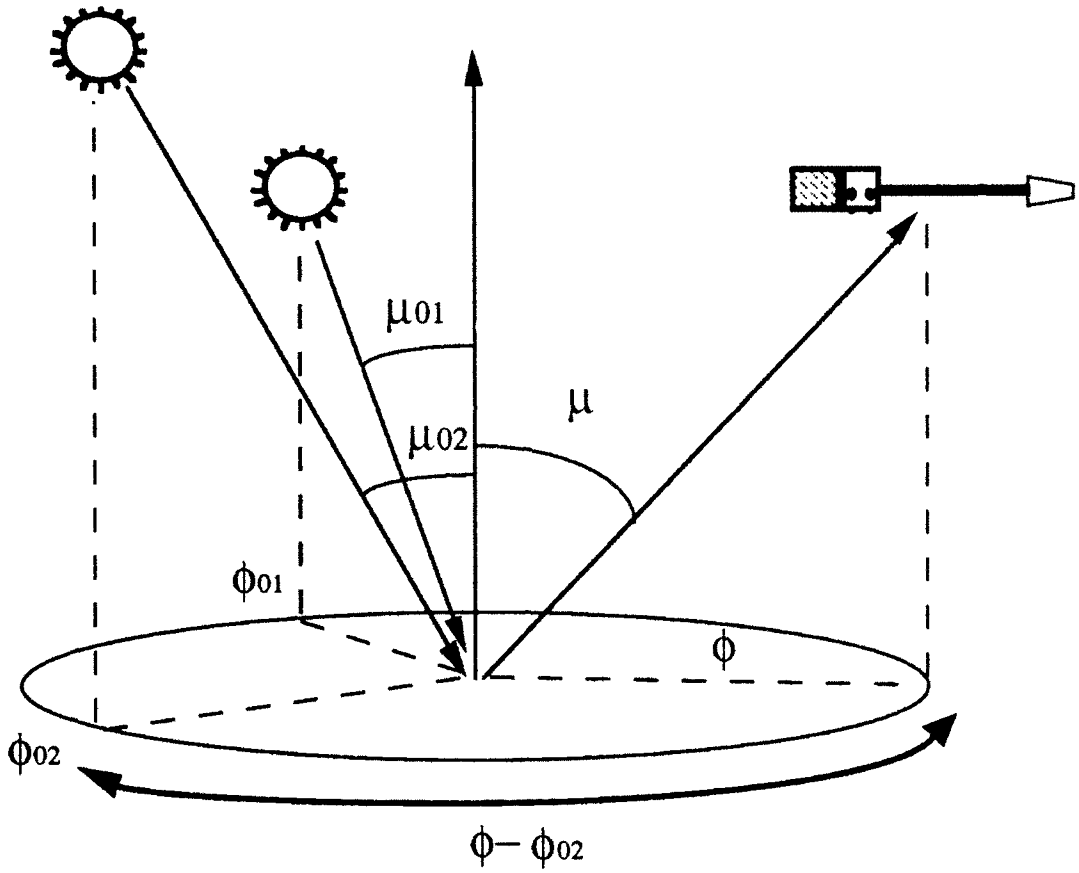

Figure 1. Viewing Geometry from Geosynchronous Orbit. μ is cosine of the polar angle, ϕ is the azimuth angle.

$$n(r) = Cr^{(1-3v_e)/v_e} \exp\left(-\frac{r}{r_e v_e}\right)\mu \qquad (3)$$

In line with other researchers retrieving effective radius of marine stratus, [5] we have chosen a value of 0.111 for v_e. The retrieval of the effective radius of the cloud particle size distribution is the target of this study.

Radiative transfer calculations were performed using the multiple scattering code DISORT. [13] This general purpose implementation of the discrete ordinate method permits vertically inhomogeneous, nonisothermal, plane parallel atmospheres that includes scattering, absorption, thermal emission, and bidirectional reflection and emission of the lower boundary of both diffuse and parallel beam radiation. Problems with ill-conditioning have been solved in this version. The scattering parameters were computed with a widely available Mie code [14] using tabulated complex refractive indices.[15]

Strictly speaking, the intensity of the reflected radiation from the clouds is a function of both the cloud optical depth, and the effective radius. However, channels in the visible wavelengths are predominately sensitive to optical depth, and the near-IR channels are more sensitive to effective radius.[3] Indeed figure 2 shows that to be the case with 3.9 µm radiances. The sensitivity of the cloud reflectance to optical depth is apparent only for small cloud optical depths, and then only for small effective radii. With the effective radius greater than 6 µm or optical depths greater than 10 at any radius, there is no change in the cloud reflectance. Therefore, if care is taken in using the visible channel to assure that the clouds are bright, therefore optically thick, no explicit optical depth retrieval is required to retrieve effective radius.

3. SOURCES OF DATA

There is to date only one instrument in geosynchronous orbit that has a channel in the 3.9 μm region, that being the Visible Infrared Spin Scan Radiometer (VISSR) Atmospheric Sounder (VAS) on the Geostationary Operational Environmental Satellite (GOES). This is an instrument that has one visible and twelve infrared channels. The typical imaging mode involves simultaneous imaging with the visible at one km nominal subpoint resolution, 11 μm IR imaging at 8 km resolution, and two other selectable IR channels at 16 km resolution. Normally the majority of the earth's disk is imaged every half-hour.

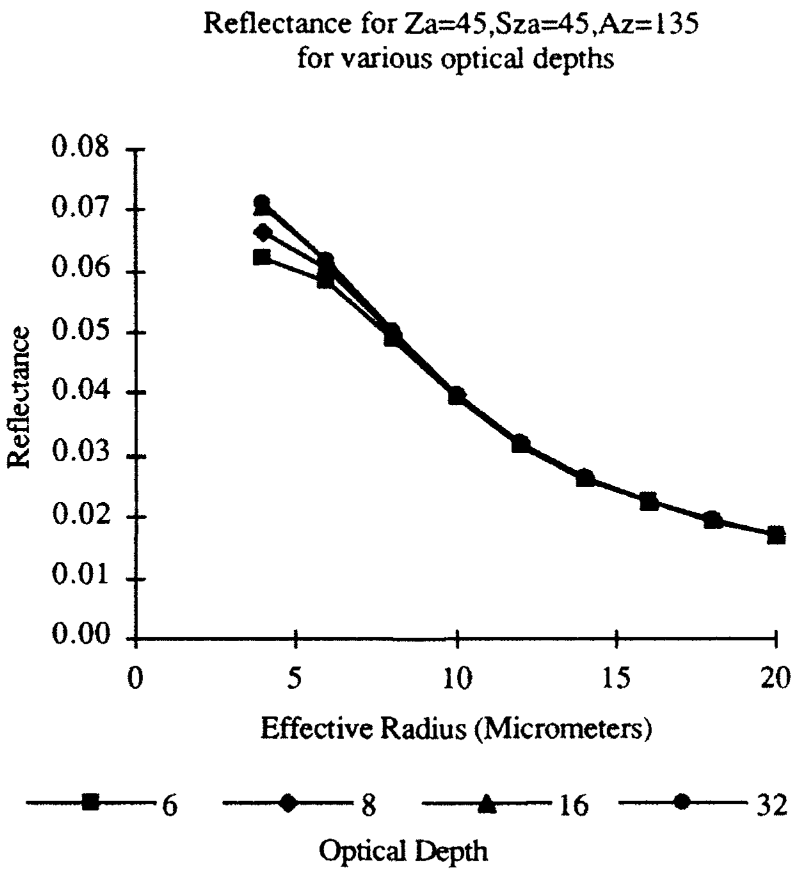

Figure 2. Reflectance as a function of effective radius for four different optical depths. Here reflectance is expressed as the ratio of reflected over incident radiance.

The preferred case study for validation of this method would be to use GOES data from the First ISSCP Regional Experiment stratocumulus IFO in July 1987,[16] which would allow intercomparison with *in-situ* aircraft observations. At that time there were two GOES satellites, GOES 6 at 135W, and GOES 7 at 75 W. GOES 7 had just been launched a few months earlier and was the first truly operational VAS instrument in the sense that the full 10 bits of IR radiances were being transmitted in imaging mode, rather than a truncated 8 bit value (this is known as Mode AAA [17]). Unfortunately, NESDIS did not have the resources at that time to support two satellites in the Mode AAA format. Therefore, GOES 6 was providing imagery only in the visible, and the 11 μm IR window. The view angle from GOES 7 to the California coastline was too oblique to be useful.

In February 1992, NESDIS began hourly imaging in the 3.9 μm band to support cloud phase discrimination for STORMFEST.[18] This imaging schedule has continued to the date of this writing. Prior to this time 3.9 μm imagery was taken only twice per day. Furthermore, GOES 7 is positioned at 112 W because the imager on GOES 6 had since failed, and NESDIS is operating with a single geosynchronous satellite. The more westerly location of this satellite provides a very good

viewing angle for studies of persistent coastal California stratus. With the readily available hourly data, it is now possible to perform a test of the technique for removing the thermal effects of daytime 3.9 μm radiances.

Data were collected at the Geophysics Directorate during the period 21 July to 31 September 1992 in a sector centered on 35 N 125 W. Visible, 11 μm and 3.9 μm infrared imagery were collected during the daylight hours during this period. All data were collected at the instrument spectral resolution, which was six bits for the visible, and 10 bits for the infrared. The period from 12 to 18 August was identified as particularly suitable for it's persistent, opaque stratus in the area of interest. With the exception of 15 August, which had considerable overrunning cirrus, this period will be the focus of this study.

4. RETRIEVAL PROCESS

The cloud reflectances were computed for the viewing geometry from GOES 7 to the area of interest for this time period using the multiple scattering code DISORT. The range of viewing angles used was: satellite zenith angle 35,55(5), solar zenith angle 12.5, 77.5(5), azimuth angle 80,175(5), and the range of effective radius was 2,20(2) and 32. The optical depth used was 16. Reflectances at intermediate angles were determined by linear interpolation. The effective radius retrieval is performed by minimizing the function

$$M = \left| \begin{array}{l} \{I_1(R_e,\mu,\varphi;\mu_0,\varphi_0) - I_2(R_e,\mu,\varphi;\mu_0,\varphi_0)\} \\ -\{U_1(R_e,\mu,\varphi;\mu_0,\varphi_0) - U_2(R_e,\mu,\varphi;\mu_0,\varphi_0)\} \end{array} \right| \tag{4}$$

with respect to the effective radius, R_e. In this expression I is the measured radiance, U is the computed radiance, μ is the cosine of the zenith angle, φ is the relative azimuth, the subscripts 0 refer to the solar angles, and the subscripts 1 and 2 refer to the two different viewing times. The mapping between the radiance difference and effective radius is given in figure 3. This figure is strictly valid only for 12 August 1992 at 35N, 125W. Other locations will have different viewing geometries, and this mapping function will vary somewhat. In particular, the mapping function for 1730-1830 in figure 3 has a near indeterminacy at about 15×10^{-5} W m^{-2} sr^{-1}. The mapping function has a very steep slope here which makes the retrieval very uncertain for small effective radii. It is unclear at this time why this steep slope in the mapping function is peculiar only to this part of the 1730-1830 radiance difference.

The extraterrestrial solar irradiance was taken from the LOWTRAN 7 data base.[19] The atmospheric transmittances were computed on a daily basis with MODTRAN,[20] using the radiosondes at Oakland, Vandenberg AFB, and San Diego. These transmittances were then averaged and used for all retrievals. There was very little variation in the transmittance among stations, or over the period of the week.

Three time intervals were chosen for the retrieval process: 1530-1630, 1630-1730, 1730-1830 UTC. The total range of time corresponds to 0730-1030 Pacific Daylight Time. Retrievals were performed independently on the three time intervals. The radiances were pre-screened using collocated visible counts and 11 μm radiances for clear ocean, sub FOV broken stratus, thin cirrus and thermal invariance. Contour plots of the retrievals are for 12 August are presented in figure 4.

The contour plots of the retrievals from the three time periods are qualitatively quite similar. There is a maximum of about 12 μm near the center of each image, and another maximum of 15 μm in the upper left. There is another region of high R_e off Monterey Bay and Big Sur which seems to persist through the period. The region bounded by the 6 μm contour line is somewhat conserved among the time intervals. There is, however, considerable variability in the retrievals. This variability has also been noted by other researchers on different days and on different aircraft flights.[21,4] It is important to note, however, that the aircraft data presented by these studies cover the area of only a few pixels at the resolution of the VAS.

5. ERROR ANALYSIS

The error in the retrieval process was simulated by Monte Carlo methods. The expected radiances were computed for each effective radius. These radiances were then perturbed with measured gaussian instrumental noise of 1×10^{-5} W m^{-2} sr^{-1} [22] and used to retrieve the effective radius. Each realization used 10,000 samples. The standard error of the simulated retrieval

is plotted against the true value in figure 5. To estimate how the actual retrieval performed, small contiguous areas were manually selected from the larger retrieval areas, and the mean and standard deviation of these small areas were then computed and also plotted in figure 5. The sample sizes of these small area range from about 20 to about 100 individual retrievals. The comparison of the simulated retrieval variance with the actual retrieval variance is quite good.

Figure 2 gave the relationship between radiance difference and effective radius. It is clear that there is an inverse relationship between these two parameters, the greater the radiance difference, the smaller the particle. It follows that for small radiance differences, a given random noise value will cause a large variation in the statistics of the retrieved radii. Hence, there is greater uncertainty in large retrieved effective radii than for small radii. Although there is considerable scatter in figure 5, it brackets the expected values nicely.

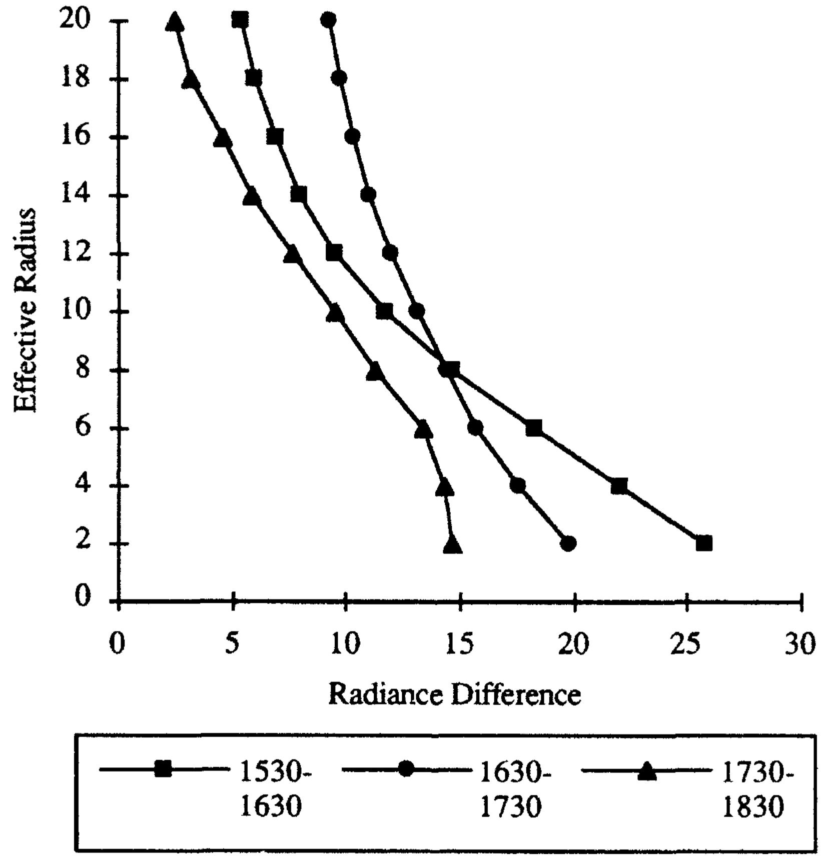

Figure 3. Relationship between radiance difference and effective radius of the cloud. Effective radius is in μm, and the units of radiance difference is W $m^{-2}sr^{-1}x10^5$.

6. CONCLUSIONS

A method of removing the thermal component from near-IR radiances has been presented. The resulting solar component of the scattered solar radiances was used to retrieve the effective radius of persistent coastal California stratus for a case study in August 1992. Unfortunately, there was no *in situ* observations available for comparison. However, the range of the retrieved values compare favorably with other published results.[4,21]

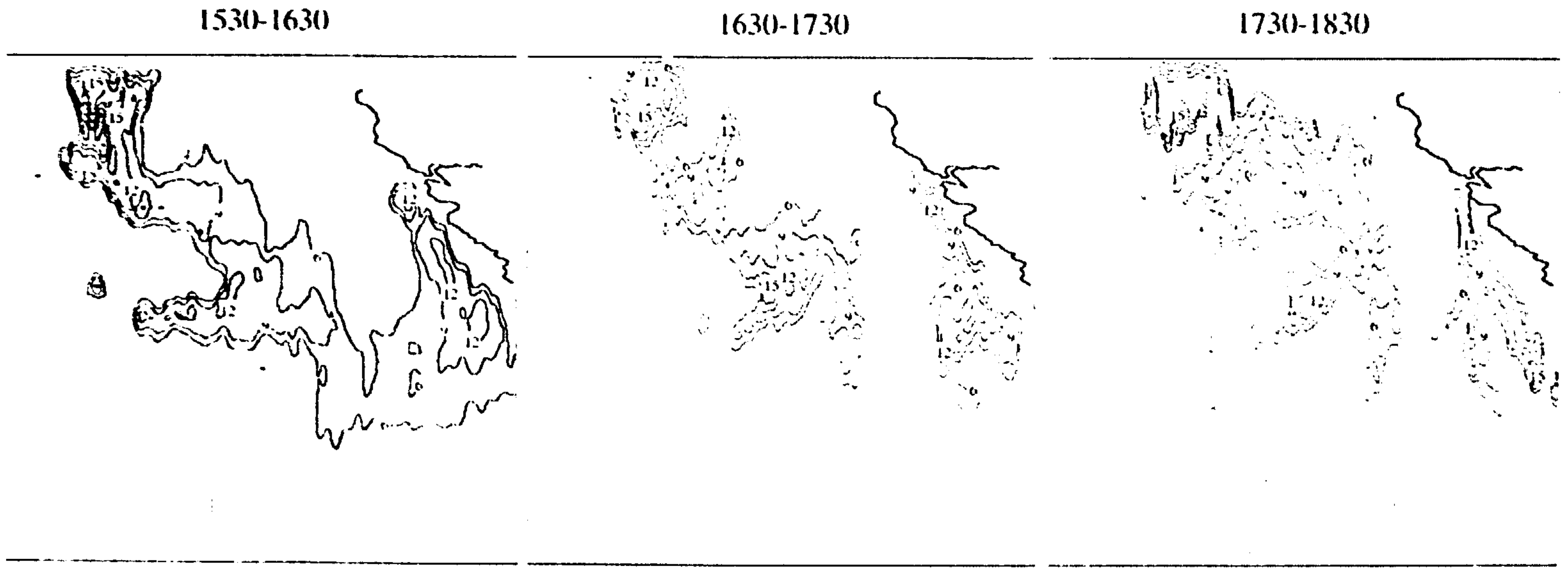

Figure 4. Effective radius retrieval for 12 August 1992.

Effective Radius Retrieval Errors as a Function of Radius

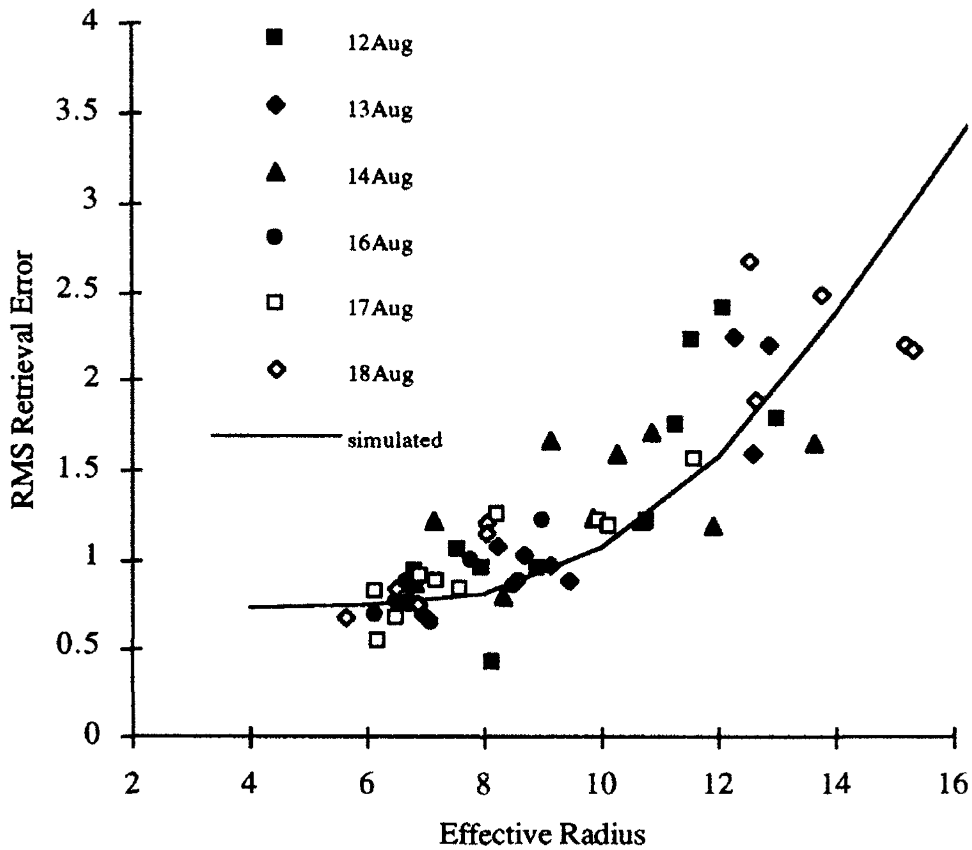

Figure 5. Effective radius retrieval errors as a function of radius. Solid line is the expected value using Monte Carlo simulations. The individual points represent values from contiguous retrieval points on the indicated days.

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